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In this work we explored the design of high strength low weight actuators based on vibratory kinematics. We developed a mathematical model for a linear motor based on standing wave vibrations and built versions of such devices using both magnetostrictive and electromagnetic actuators. Our analysis and our implementations show that such devices can be made to work. We include in this report suggestions as to how to further enhance the performance of this type of system.

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LIGHT WEIGHT HIGH PERFORMANCE MANIPULATORS

FINAL REPORT

ROGER W. BROCKETT

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HARVARD UNIVERSITY

Final Report

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The purpose of this document is to report the implications of our findings for the design of high strength, low weight, low volume actuators suitable for use in robotic devices. We will describe the results of our experimentation and recall some of the main points of the published work which grew out of this effort. The work reported here was carried out between April 1, 1985 and March 31, 1988. The experimental effort was devoted to the development of actuators which utilize fundamentally new principles. Accomplishments include what we believe to be the first published analysis of standing wave linear actuators and the first construction of a standing wave motor using terfenol clamps and electromagnetic drive.

1. The Physics of Motion Generation

Electric motors are the actuation mechanism of choice in the majority of robotic applications. Because they are self contained and easily integrated with contemporary solid state electronics, electric motors have replaced hydraulic and pneumatic actuators in most situations. However, because these devices only achieve reasonable power densities at high speeds they are far from being ideal. The use of gears for speed reduction inevitably leads to backlash with an attendant loss of controllability. The availability of high energy product rare earth permanent magnets, such as the samarium-cobalt and neodymium-iron-boron magnets, has resulted in a significant increase in the maximum torque level. Ultimately, however, the torque limitations in variable reluctance motors derive from the fact that magnetic forces are limited to about 200 pounds per square inch by the saturation flux of soft iron (about 2000 Gauss) and the fact that in those electric motors for which **iXB** (current cross magnetic field) forces dominate, the current in the windings is limited by the ability of the structure to withstand the temperature differential needed to generate the heat flow necessary to dissipate the energy associated with ohmic heating.

Quite recently there has become available new types of actuators based on the piezoelectricly induced strain exhibited by certain types of polarized ceramic materials such as lead titanate and lead zirconate. Piezoelectric actuators, after having been used for years in highly specialized applications, such as driving the stages of electron microscopes, have recently appeared as competitors in markets previously held by ordinary electric motors. Although the force generated by the piezoelectric effect can be large, the corresponding strain is small. The product of the force and displacement is such that high frequency operation (> 10,000 hz) is essential if one is to achieve reasonable power densities. Thus piezoelectric design requires high precision engineering and careful consideration of all possible modes of high frequency elastomechanical vibration associated with the structure.

In addition to magnetic and piezoelectric actuation, this report will discuss magnetostrictive actuation . The magnetostrictive effect has been studied in common magnetic materials, such as nickel, for about one hundred and fifty years. Until recently this effect has not been of much technological interest because for most materials the magnetostrictive effect produces a change in length of at most five parts in 100,000. In the last twenty years new materials have been discovered which exhibit magnetostrictive strains of forty times this size, i.e. two parts per thousand.These strains are seen in certain alloys made by combinding iron, and the rare earths terbium and dysprosium. The manufacturing technology necessary to produce such materials in quantity has been brought to the point where there is now a commercial product, Terfenol-D, which exhibits strains of this magnitude. Actuators based on this family of materials have already found some use in underwater sound generation and further applications are being pursued.

The following table organizes some relevant aspects of the physics associated with magnetics, piezoelectrics, and magnetostrictive energy conversion. The numbers in this table suggest a greater precision than is warranted since we omit the discussion of many details which can significantly affect the performance. Moreover these numbers are merely indicative of the absolute upper limits associated with the various effects; packaging and other considerations may mean that actual devices could never approach these limits. For example, the third column indicates a high frequency cutoff for each effect. This number like the others given, is subject to interpretation since there is in each case a gradual fall-off of the effect at high frequency. Notice that it is the product of the first three numbers which determines the power per unit volume and this number displays more consistency than the others. Finally, observe that both magnetic force generation and magnetostrictive force generation require electrical coils having significant volume. Because this table ignores this, these effects will not, in applications, enjoy the advantage over piezoelectrics that the table suggests.

effect	**pressure**	**strain**	**frequency**	**power/vol**
variable reluctance	200 psi	.001	10,000 hz	220 watts/in^3
F = iXB		infinite	100,000 hz	thermal limit
magnetostrictive	4000 psi	.002	10,000 hz	9000 watts/in^3
piezoelectric	2000 psi	.0002	200,000 hz	9000 watts/in^3

Table 1. The force displacement characteristics of the three systems.

In addition to the coupling coefficients associated with energy transduction, the elastomechanical properties of materials may play a significant role. Because mechanisms based on surface hardness and elastic deformation are often used to solve problems associated with speed reduction, the conversion of vibratory motion to translative motion, etc. these properties can also be critical. The central issues here hinge on the strength of the materials being used, their elastic limit, and the energy storage that they are capable of when operating in a linear stress/strain mode. Since the yield strength of common materials is at least an order of magnitude larger than the pressures which appear in table one (e.g. in the range of 10,000 to 70,000 psi for commercial grades of aluminum and 85,000 to 150,000 psi for common steels) it is often possible to ignore these considerations in the design of electric motors.

2. The Kinematics of Motion Generation

The energy conversion effects cited above clearly occupy a central role but there are also geometrical constraints which are quite significant in explaining why commercial high performance motors in the 100 watt class do not have power densities greater than about 50 watts/in^3 and typically are more like 5 watts/in^3. Even motors in the 10,000 watt class rarely achieve power densities of 100 watts/in^3. The explanation is as follows. Except for the **iXB** force motors in table one, all the transduction effects described in the previous section are small strain effects which require high frequency operation if they are to deliver reasonable power densities. This means that in order to create motion on a scale which is, say, two orders of magnitude larger than that available directly from the strain effects it is necessarily to synthesize gross motion from a series of small motions. This building up process must be done by a controlled application of shear forces, as it is in salient pole electric motors, by momentum transfer as in turbine engines or by means of a piston/crank shaft mechanism as in piston engines. The torques produced via latter mechanism are limited by the product of the available force times the displacement, making this an unrealistic possibility for small strain mechanisms. Although momentum transfer is used in the small piezoelectric motor recently introduced by Micro Pulse Inc. of Santa Barbara [8], **F = iXB** and controlled shear are the most common choices for motion generation. This makes the frictional shear piezoelectric motor now being marketed by Panasonic Inc. [7] especially interesting.

Motors must ultimately produce relative motion between two rigid bodies--i.e. the base of the motor and the output shaft or bar. The interaction may be mediated by an entity without fixed shape, e g. a gas, a fluid or a field, or it may arise as a result of interaction between "solid" objects one or more of which is undergoing strain, the interaction being described by the laws of elastomechanics and/or the laws of friction. Electromagnetic motors and steam turbines are examples of the first situation whereas the piezoelectric traveling wave motors we will be discussing are examples of the second. Because the path of a rigid moving element must not be obstructed by a second rigid element, and because forces must react against something, either the motion is reciprocating or else there is a nonzero angle between the force vector and the velocity vector. This is true for both the solid-solid interactions and solid-gas, fluid or field interaction. The size of this "clearance" angle, the angle necessary to allow the moving element to clear the fixed source of the force, is important in determining the maximum force or torque that the actuator can produce. We want to argue that it is useful to divide the set of all actuators into two groups, those for which the energy transduction process is primarily through forces which are aligned with the motion ("piston-type") and those for which the forces are largest in a direction perpendicular to the motion ("turbine-type"). In the first instance the motion must be vibratory whereas in the second it can be rotational or translational. Since shear is the term from mechanics which is used to describe displacements which are orthogonal to the direction of applied forces we may think of the classification as being equivalent to a taxonomy which puts rotary/shear machines in one category and vibratory machines in another. This classification is common in some parts of engineering thermodynamics; we think it lends insight to our present discussion as well.

We have argued that the magnitude of the shear forces are very important. In particular it is sometimes useful to focus on the ratio of the maximum shear force in relationship to the normal component of the force vector. In the extreme case of interlocking objects, the shear forces are limited by the yield strength of the interlocking material. On the other hand, if it is patterned but patterned in such a way as to permit certain relative movement, such as movement of a rack and pinion, there will be constraints on the pattern. A second possibility is that of two solids rolling together without slipping on each other. In the case of flat surfaces this can occur by virtue of the effects of a certain coefficient of friction or it can occur with topographically patterned surfaces. This is meant to include patterning of the physical properties of a flat surface such as a flat surface which is patterned with lines of ferromagnetic material separated by lines of nonmagnetic material. In such cases one can define a coefficient, analogous to the coefficient of friction, thereby defining the limiting ratio of the tangential force to the normal force. We remark in passing that for flat surfaces interacting through magnetics with the relative permeabilities being, say, 4000 and one, (soft iron and air) we have found the ratio of tangential component of the magnetic force to normal component of the magnetic force to be limited to about .1, a number significantly smaller than the expected range for static friction. Finally, consider turbine-type motion generation. Here one has a flow of particles which strike a blade and, through momentum transfer, the blade is caused to turn. The angle between the line of motion of the flow of particles and the direction of the movement of the blade maybe 90 degrees but because of the orientation of the blade and because the geometry, force is generated in such a way as to do work. In summary, whenever two rigid objects move relative to each other their interaction is characterized by a ratio of the normal force to the tangential force and this is limited by the frictional, elastic, magnetic, etc. properties of the patterned material.

3. Coupled Wave Actuators

We have argued that the transducers which are most attractive from the point of view of power density do not have large enough strains to be used in piston/crank shaft mode. This suggests that they will most useful when they are combined with some coupling mechanism which couples them with motion on a larger scale. In an electrical power setting there are a variety of common ways to pass from a vibratory excitation (alternating current) to a steady motion (direct current). Both the standard AC motors and rectifying diode can be thought of as fulfilling this function. We are going to argue that thinking of actuation mechanisms in terms of nonlinear wave phenomena, although unconventional, can be a useful point of view. This is particularly true in view of the new traveling and standing wave actuators which have recently been developed and which form the core of this research.

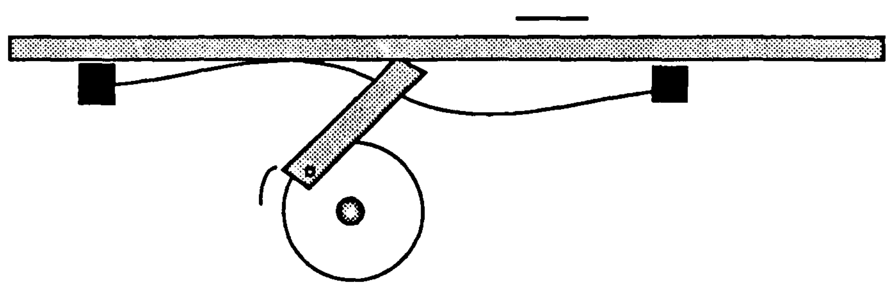

Figure 1. A Wave mechanism for rotary to linear conversion

The operation of harmonic drives involves elastomechanics rather than just rigid body kinematics because the main drive element is under constant elastic deformation. Harmonic drives have become popular in recent years as a means to obtain high ratio gear reduction (say 200:1) in a single stage. Such a large reduction can not be achieved in a single stage with rigid gears because of a combination of strength of materials problems and because of the tolerances which would be required. Some of our efforts have been devoted to mimicking the harmonic drive with magnetics. However the performance limitations of the common speed reduction devices used with electric motors, be they conventional gear trains or harmonic drives, are significantly affected by yield strength.

In order to create small, high torque, electromagnetic motors we sought to come up with a design in which the "radial" forces would do work. One design which achieves this is the piston-type steam engine. In that case the full gas pressure does do work. There are very high d'Alembert forces associated with the accelerations necessary to reverse the the direction of the piston. A problem with this analogy is that unlike the force generated by steam pressure on a piston, the force generated by a magnetic field falls off with distance thus limiting the "stroke" length to a small fraction of the length of the magnetic circuit. Because in the standard piston/crank shaft geometry stroke length is twice the lever arm, there exists a precise limit on torque production based on this mechanism. For these reasons we looked for a geometry which would allow us to apply directly the full magnetic pressure using small displacements at high frequency .

4. New Electromagnetic Motors

Considerable progress has been made in recent years in the design of DC motors. This has been due to the emergence of better magnetic and electrical designs; the development of better permanent magnets (especially samarium-cobalt and neodymium-iron-boron magnets); and the use of more sophisticated driver electronics, e.g. brushless designs. One development that has proven to be useful is the use of permanent magnetics to bias magnetic circuits so that they operate not at zero average flux but rather about a non zero operating point. Usually this involves the use "flux steering" i.e. the use of a electrical current to augment the flux in one of two or more paths of a magnetic circuit. The main advantage here centers on the fact that the force in a magnetic circuit is proportional to the derivative of the flux times the magnetomotive force; if the flux and magnetomotive force are not zero then this derivative has a larger value. This has been exploited in the so-called Sawyer motor designed at IBM [4]. A key issue in the manufacture of actuators involves the tolerances required in their fabrication. Magnetic motors are attractive in this regard because no dimensions, except those of the bearings, are especially critical; clearances of .01 inch are typical. In well designed magnetic circuits, the magnetic force falls off rather slowly with displacement as compared with the other actuation mechanisms to be considered here. Since the reluctance of a magnetic circuit is proportional to the volume of the air gap (with an offset); a rule of thumb for the force as a function of displacement x is $F=F(0)/(a+x)$ with a being roughly .001 times the length of the magnetic circuit.

As mentioned above, the main problem with conventional electric motors, insofar as robotic applications are concerned, lies in the fact that they achieve reasonable energy densities only when they are operated at high speed. The infeasibility of high torque, low speed designs is the result of the fact that magnetic attraction in all "non exotic" situations is limited to about 200 Lbs. per sq. in. because of the saturation flux level in soft iron. Something close to this pressure level is achieved in well designed commercial motors (See, e.g. the Motornetics motor specifications [5]) but it is only achieved when it is associated with a force directed in the radial direction--a force which does no work. The forces which do do work, the forces in the tangential direction are only about one twentieth of the size of the radial forces. Efforts to improve this highly unfavorable ratio are frustrated, for the most part, by the fact that in contrast with the situation which one finds in the study of electric fields in which the ratio of the conductivity of a good conductor to that of a good insulator is about 20 orders of magnitude, the permeability of free space is only down by a factor of 1/4000 from that of soft iron and hence a considerable amount of fringing occurs in magnetic circuits which have small scale features. VLSI magnetics is not a possibility with the materials which are known today.

4.1 The Electromagnetic Rocker

This device is a prototype electromagnetic piston, representing what might be termed a pure variable reluctance machine. It produces vibratory motion and generates forces in the direction of motion which are approaching the 200 psi limit. We describe the basic setup here; an application will be described in the next section.

The rocker uses a permanent magnet and an electromagnet to rock a "toggle" piece from one side of a U-core to the other. The diagram below shows the rocker with the toggle piece in an intermediate position. The permanent magnet is a samarium-cobalt magnet, and both the U-core and the toggle piece are made of soft iron. One each half of the core is a wire coil (see Figure 2).

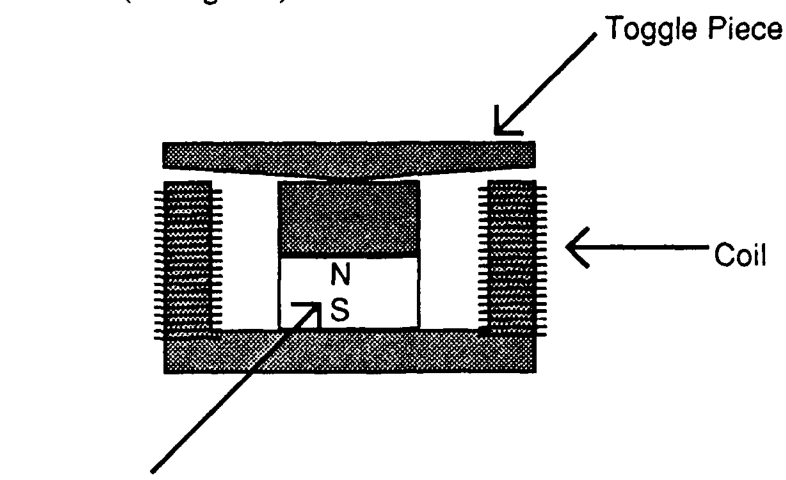

Figure 2: The Rocker

The paths for the magnetic field lines when the rocker is in the intermediate position are shown below in figure 2.

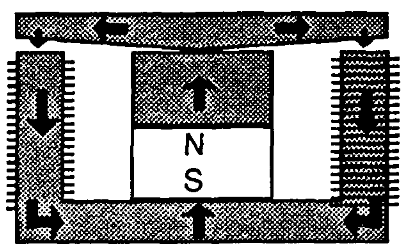

Figure 3: Magnetic Flux in Rocker in Intermediate Stage

This intermediate position is unstable, and the toggle piece leans against one side or the other. When current is then applied to the coil on the opposite side, a magnetic force is generated that switches the toggle piece from one side to the other, as demonstrated in figure 3. Sending current through the other coil flips the toggle piece back to the other side.

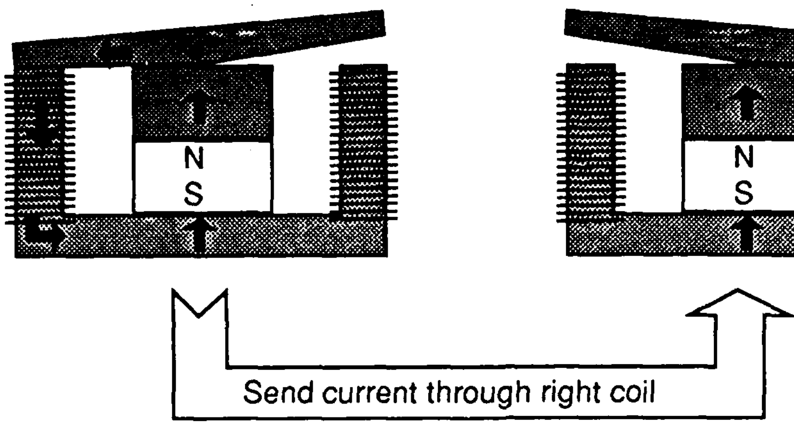

Figure 4: Flipping the Toggle Piece with Current Pulse

4.2 Electromagnetic Standing wave Motor

While one coil operates to pull the toggle piece to one side, the coil on the other side can also operate to push the toggle piece away: the current in that coil is reversed to actively oppose the magnetic field of the permanent magnet.

The moving strip (which must be magnetic) is placed between the toggle piece and one arm of the U-core. It is squeezed by the force provided by the magnetic field of the permanent magnet and the wire coil.

Our rockers measured .750" x .375" x .350", not including the toggle pieces, which measured .750" x .375" x .100". The samarium-cobalt magnets are .375" x .250" x .150", with an energy density of 30 million Gauss-Orsteads. Each coil had 350 turns, and the maximum allowable current for continuous operation was 2 amps. The moving strip was a .010" thick by .200" wide piece of spring steel.

Figure 4 illustrates the motor setup. Aluminum braces were fashioned to hold the two rockers in place, with a small slit cut in the brace to allow the moving strip to pass through. A ferrite electromagnet drove the moving strip. On occasion, as the diagram shows, an extra piece of ferrite was placed opposite the working strip to increase the force with which the electromagnet could bend the moving strip.

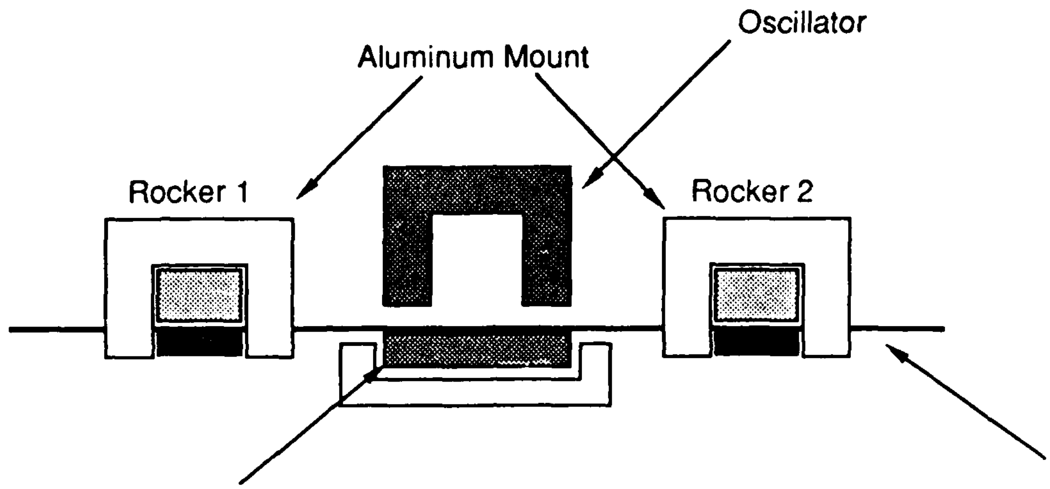

Figure 5. Rocker Motor Set-up

The table below gives typical results for performance of the rocker as a function of frequency. The amplitude of the oscillation of the strip was 1/10" and the distance between the brakes was 3".

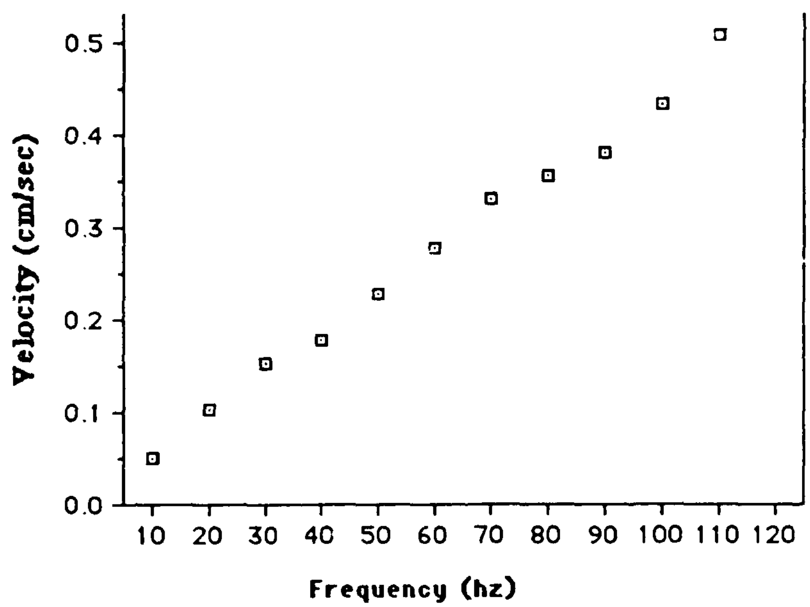

Figure 6. The frequency response of the rocker.

The pulling force was 25 grams.

Since with our design we were not able to resonate the moving strip, one limiting factor on the pulling capability of this motor was the middle oscillator. The motor's pulling capacity increased dramatically when we ran the motor with the extra piece of ferrite. This extra piece would not be practical in a motor operating at higher frequency, for the extra piece is to large to slide back and forth at the same rate as the strip. With this extra piece, the motor operated best at only 30 hz. At this frequency, it pulled with a force of 150 grams at a speed of .10 in/sec.

Using a strobe light to visualize the motion of the toggle pieces, we determined that large phase shifts are introduced into the braking action of the rocker as the frequency is increased. By using the strobe light to guarantee that the brakes were operating at the proper phase, a higher speed of .33 in/sec was achieved at 75 hz.

The highest, repeatable frequency obtained with rockers of this size and dimension was 125 hz. Higher frequencies, up to 200 hz, were seen on occasion. The rocker is very sensitive, at these upper frequencies, to whether the toggle piece is aligned perfectly on the U-core. The aluminum mounts on the motor were designed to keep the toggle piece aligned properly. They were not very successful at this task, and this failure was one of the primary causes for the inconsistency of the rocker's operating frequency.

There are several ways in which the rocker brakes can be modified to obtain a higher frequency response.

1). The gap between the toggle piece and the U-core can be reduced to a much smaller size. The original rocker brakes had a gap size of 5/100". If the gap size were reduced to 2/100", then, given 1/100" as the thickness of the moving strip, the 1/100" between the toggle piece and the spring steel strip would be more than sufficient to yield a high ratio of braking force to non-braking force.

The important drawback, though, to reducing the gap size is that as the gap size is reduced the leakage through the other half of the U-core increases. The leakage would not prevent the modification from improving the frequency response. It would, however, reduce the braking force.

Reducing the moment of inertia of the toggle piece will raise the frequency response of the rocker. It can be reduced in two ways:

2). Reducing the height of the toggle piece and therefore reduce its mass. This modification will raise the frequency response only up to a certain limit. Once the toggle piece is so thin that it is magnetically saturated, then any reduction in height, while reducing the moment of inertia, also reduces the torque that can be applied to the toggle piece by magnetic forces.

3). Make the length of the toggle piece smaller. There are two limits, however, on reducing the length of the toggle piece. First, more leakage will occur between the opposite arms of the U-core as they are brought closer together. Second, the space for the windings will be reduced.

To summarize about the modifications that can be made to the rocker, the frequency of the rocker will be increased as we reduce its size, but, of course, the braking force generated will also decrease. Given a goal for the amount of clamping force the rocker should generate, and assuming we operate the rocker with the soft iron saturated, we can calculate the cross-sectional area of the magnetic circuit. This area sets the height of the toggle piece and the area of the U-core arms. The amount of flux needed to saturate the toggle piece will also determine the size of the magnet and the number of amp-turns. From the number of amp-turns needed, we can calculate the space needed for windings, and this space would then set the length of the toggle piece.

The values given for the performance of the rocker motor are probably far below the maximum values obtainable with this design. Some initial attempts to improve the frequency of the rocker have been very successful. By reducing the gap size to 3/100" and by reducing the height of the toggle piece to 5/100", we were able to achieve a frequency of 400 hz. Perhaps even faster response is possible. The cross sectional area of this magnetic circuit is still sufficiently large so that the theoretical force obtainable with this rocker, assuming saturation of the soft iron, is 4 lbs. Compared to the terfenol brakes and other brakes that can be made with low displacement transducers (including piezoelectrics), the rocker will always have the tremendous advantage of a very high ratio of braking force to non-braking force, due to the sharpness of the difference between the open and closed states.

5. Piezoelectric Motors

From the point of view of kinematics there are three types of piezoelectric motors which have been considered: traveling wave motors, sanding wave motors and impulse motors. These are exemplified by the Panasonic rotary motor [7], the vibratory motor we have described [2] and the Micro Pulse motor [8]. We will examine these design below. Before doing so, however, we should point out that because piezoelectric elements produce displacements on the order of 1/10,000 of their length, and because the voltages required are of the order of 8000 volts/inch of piezoelectric material, it is common to assemble piezoelectric drivers as sandwiched "piezo benders" -- a structure very similar to the familiar thermally sensitive bimetalic strips found in low precision thermostats. This idea dominates the most familiar "low tech" applications. It is used in piezoelectric sound generators and load speakers, the piezoelectric droplet formation device found in some small humidifiers, etc. It is not, however, used in the Micropulse motor because in that application high force is more important than larger displacements.

The most complete product available for use today in this field is the piezoelectric motor produced by Panasonic and marketed as the USD-40 Ultrasonic Motor. This is a motor which is 40 mm in diameter and 10 mm thick. It produces about 10 inch ounces of torque at a maximum velocity of 600 rpm. It is a traveling wave motor with the traveling waves being excited by two sets of piezo electric drivers. The displacements are about 20 microns, i.e. approximately .001 inch. This means, of course, that the manufacturing tolerances must be rather precise.

5.1 Piezoelectric Benders

Piezoelectric materials expand or contract in the presence of an electric field. Circular "benders" are a common mode for using piezoelectrics. A circular layer of piezoelectric (typically lead zirconate) is bonded to a metal substrate. The piezoelectric is "poled" so as to expand and contract radially as an alternating voltage is applied across the piezoelectric's two faces. If the piezoelectric is properly mounted and fixed, then the metal substrate will bend back and forth.

We constructed a test cell to determine whether we can use two of these piezoelectric benders, mounted opposite each other, to clamp a moving strip. The strip runs between the two metal faces. When the proper voltage is applied, the two benders bend towards each other, squeezing the strip between their faces. We used a commercially available bender with disk geometry and radial poling. It was 1.6 in. (35 mm) in diameter, and had a resonant frequency of 2800 hz. Typically one of these benders produces a maximum displacement of about .0001 in.

From our tests, it is clear that this displacement is not sufficient to clamp a moving strip and release it during each bending cycle. That is, such a strip can not be clamped and released 2,800 times per second. Instead, we observed that during the period in which power is applied to the bender there is a significant decrease in the friction between the bender faces and the strip as compared with the friction present when the power is off. The ratio of the frictional force in these two situations is approximately 2 to 1.

We have one hypothesis to explain this effect. The coefficient of kinetic friction is often significantly lower than the coefficient of static friction for a given system. When the alternating voltage is applied at 2800 hz, perhaps the bender faces oscillate sufficiently to make the coefficient of friction the coefficient of kinetic friction.

The question, then, is whether an bender with a natural frequency f_r can be operated as a brake with frequency f_b, where $f_b << f_r$. In other words, for half of each cycle of the brake, the piezoelectric would bend f_r/f_b times at frequency f_r, and during the other half of each cycle the piezoelectric would be turned off. At present, we know little about the feasibility of such a design, but it would be easy to test. Determining the ratio f_r/f_b would be one critical experiment, and most likely that ratio would be high enough to require us to use ultrasonic piezoelectric benders.

There are two limits to a brake of this design. First, with ultrasonic transducers, the amplitude of the oscillation may be insufficient to generate this same effect. Second, if the brake takes too long to settle after the half of the cycle when the piezoelectric is active, then the brake frequency f_b may be severely limited.

6. Magnetostrictive Motors

We have built a standing wave motor in which the clamping action is provided by normally closed clamps which are opened by sending current through a coil which surrounds the magnetostrictive material Terfenol-D. The moving strip is made of spring steel and is deflected by an electromagnet. At present, this system produces 300 grams force and moves at 10 in/min, while operating at 250 hz, but these numbers are not, in our opinion, indicative of the ultimate capability of such a device. Initial attempts to operate the motor at higher frequencies have so far failed, but we have evidence to believe that it can be operated at at least 500 hz.

The following is a side view of one of the Terfenol-D clamps (the moving strip travels through the indicated slot, into the page). The soft iron core provides a closed magnetic circuit. The spring preloads the terfenol and keeps the working strip clamped while the brake is off. When current is sent through the coil, the terfenol expands, lifting the aluminum/spring steel lever arm and releasing the moving strip.

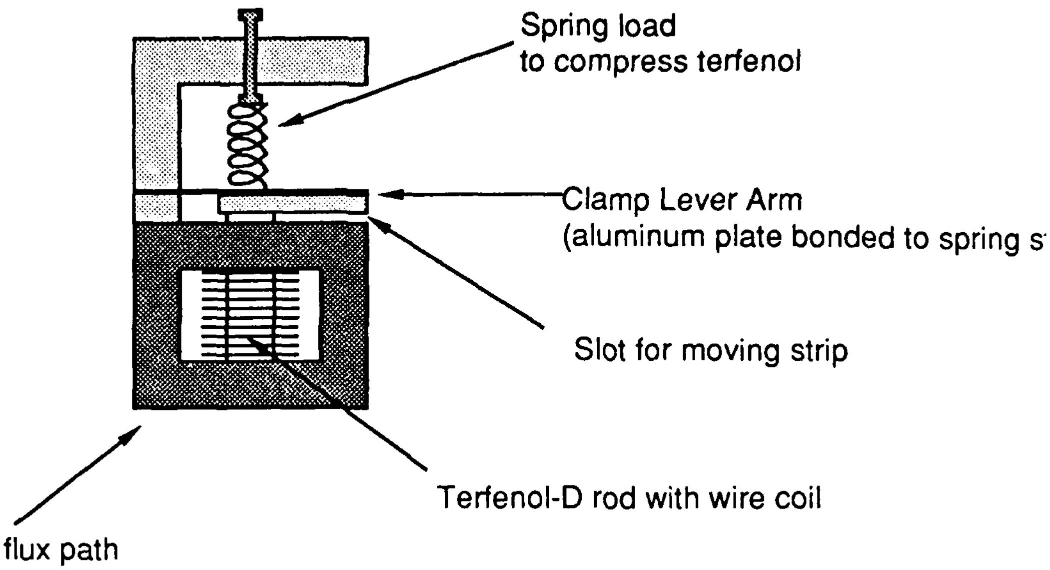

Figure 7. Terfenol-D Clamp

The Terfenol-D rod is a cylinder .5" long and .2" in diameter. The rest of the clamp is .5" wide, .9 " long, and 1.8" tall. Each coil has 125 turns, and the maximum allowable current for continuous operation is 4 amps.

The maximum strain of the terfenol, 2 parts in 1000, can be achieved only when the terfenol is preloaded with about 2,000 psi of compressive force. In our design, we use a stiff spring to apply this preload. Our preload is significantly less than 2,000 psi, perhaps only 500 psi, and therefore we are not obtaining the ultimate performance.

To test the performance of the terfenol brakes, we used a laser, a mirror, and a photodiode to measure the motion of the lever arm. The laser beam is reflected off of a mirror attached to the lever arm. As the lever arm moves, the laser beam is deflected along a different path. A photodiode placed in the path of the beam detects the variation in light level. The displacement of our lever arm is sufficiently large to make detection of its motion relatively easy and repeatable with this setup. Unfortunately, nonuniformity of the laser beam prevents us from assuming a linear relationship between change in light intensity, as measured via the photodiode, and displacement of the lever arm.-

Our experiments show that the brakes functions far less effectively at 2,000 hz than at 200 hz. With any magnetic device, eddy current losses within the magnetic circuit place a frequency limit on the device. At 2,000 hz, the brakes are operating in the region where eddy current losses become significant. Of course the solution to the problem of eddy current losses is to use laminated steel or ferrite cores since the eddy current losses are reduced as the cross-sectional area of individual magnetic paths are reduced. This solution is not easily applied to the present situation however. The terfenol rod we use is the thinnest terfenol rod that is commercially available. Industry contacts indicate that the fabrication of thinner terfenol rods is of great interest but progress in this area has not been reported.

In the photodiode traces, especially the higher frequency traces, spikes are superimposed on the overall square wave waveform. These spikes grow larger in amplitude as the frequency increases. Once we reach a frequency at which our measuring device had sufficient resolution to capture individual spikes (around 200 hz), it becomes evident that the spikes are always the same frequency, about 8200 hz. We speculate that these spikes are the result of a mechanical resonance associated with the terfenol rod. The sudden retraction of the terfenol due to cessation of current is analogous to effect obtained in releasing a stretched spring. The spring vibrates until frictional losses damp out the vibrations. This damping out of the vibrations is evident in the traces for 10 hz and 40 hz. The time constant for damping is apparently too large to allow us to observe it at higher frequencies.

Using our laser-photodiode setup, we measured the response of the terfenol rod as a function of the magnetic driving force. The graph below gives the change in light intensity at the photodiode as a function of amp-turns when the brake is operated for short periods (to prevent overheating of the coils):

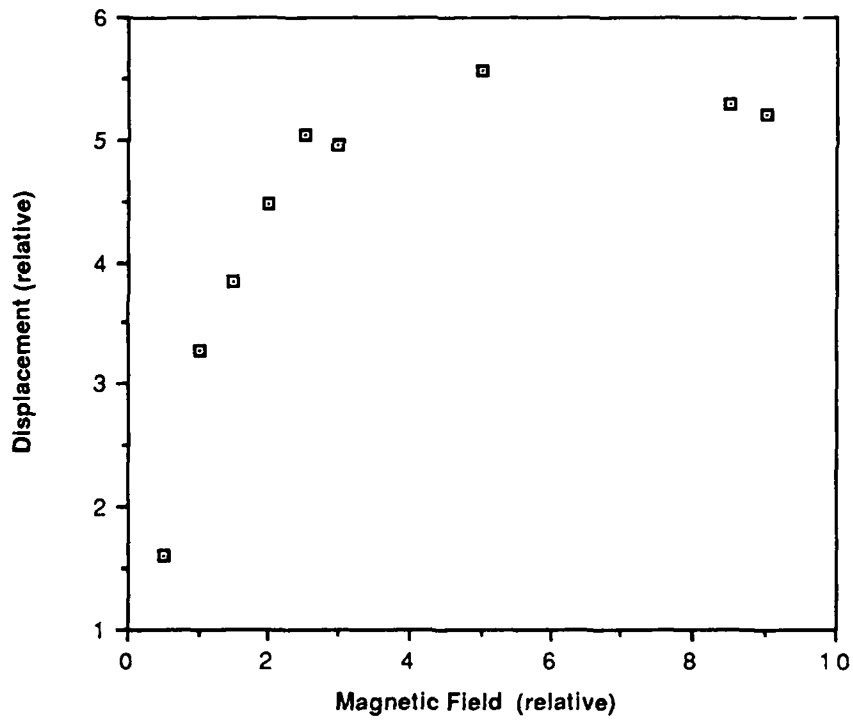

Figure 8. The magnetostrictive effect.

With the present wire coils, we are able to run the brakes continuously with about 500 amp-turns. The graph indicates that 500 amp-turns is not enough of a driving force to saturate the terfenol and to obtain maximum response. We are, however, operating near that region, and therefore we should not be too concerned, in a later design, with increasing the volume available for the coils.

A significant limitation of the present motor is the inconsistency of the motor's action due to the nonuniformity of the moving strip. The size of the slot for the moving strip is carefully set using an additional screw (not shown in drawing) that pushes against the bottom of the terfenol rod. This adjustment is exceedingly critical for proper functioning of the brake. If the slot is too large, then the moving strip travels freely through the slot even when the brake should be clamped. If the slot is too small, then the terfenol cannot expand sufficiently to lift the lever arm off the working strip. But for any given slot height that has been set optimally for one part of the moving strip, there may be another part of the moving strip which is thinner or thicker due to uneven wear, a small burr, dirt, or a slight bend in the strip. When this portion of the moving strip enters the slot, the brake will fail. If the moving strip is thicker, it will become stuck in the brake at that point. If it is thinner, then the strip will invariably slip at that point. The latter case would lead to very deceptive results (on the low side) for the pulling force for the motor. This problem would be less significant if greater displacement were attainable from the lever arm, but we cannot necessarily hope to achieve that aim.

Taking all these points into consideration, the future of the terfenol motor is unclear. If a new form of terfenol is developed which can be manufactured into thinner rods with longer lifetimes, then the future for terfenol motors looks bright. Otherwise, eddy current losses and breakdown of the terfenol will set a discouraging limit on the operating frequency. We have not yet approached this limit, however, with our present design. If we can eliminate the mechanical ringing, then we will be in a better position to operate the motor at higher than 250 hz.

7. The Next Steps

In the literature one already sees references to "solid state motors". Not with standing the oxymoronic character of this, there is an attractive idea here. How feasible is it? In the first place we see that if it is to be based on piezoelectrics then it will necessarily be a high frequency device with small displacements. The key element will be the rectification mechanism which converts the high frequency, low amplitude oscillation to rectilinear motion. The present mechanisms for doing this all involve rectification by friction and thus understanding friction in dynamic, vibratory settings becomes a critical problem. Issues to be resolved include understanding the tradeoffs between using hard interfaces, say tungsten carbide against hardened steel, verses stainless steel against polyimide. It is clear that the frictional surfaces must be protected from extraneous materials and they must wear in a predictable way, and they must engage and release over the range of at most 10 microns but beyond these generalities not much can be said with certainty.

In the 1940's electrical engineers were faced with a whole new set of problems which arose out of radar and involved the generation and transmission of electromagnetic waves in the millimeter range. This lead to the study of traveling wave tubes, wave guides, nonlinear frequency conversion, etc. At the present time we may be on the threshold of a similar revolution involving higher frequency low amplitude electromechanical engineering. The piezoelectric elements are the new technology, the need for small, high force actuators in a wide variety of intelligent machines is the incentive. Up until now mechanical engineers have paid little attention to vibrations above the audio frequencies. Vibration engineers making fatigue studies etc. explore lower ranges. If the problems we are discussing are to be solved we need to research the higher frequency range.

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9. INTERACTIONS WITH ARMY PERSONNEL

1. On May 6-8, 1985, the Principal Investigator gave a three day short course on Robotics for army personnel at BRL, Aberdeen Proving Ground.

2. In the period June 25-June 28, 1985, the Principal Investigator participated in the Army Workshop on Kinematics, Dynamics and Control of Mechanisms and Manipulators held at Troy, New York and gave a paper entitled "The Geometry, Kinematics and Dynamics of Electric Drives."

3. On June 14-16, 1986, the Principal Investigator gave a short course on Control Issues in Robotics for army personnel at ARDC, Dover, New Jersey.

4. On October 15, 1987, the Principal Investigator participated in the Army Mathematics Steering Committee meeting at Dover, New Jersey, and visited Norm Coleman's Robotics Laboratory at ARDC.

5. On February 9, 1988, the Principal Investigator participated in a Robot Control Workshop at ARDC, Dover, New Jersey, convened by Dr. Norm Coleman.

6. In addition, we have interacted with Dr. Robert Rosenfeld of DARPA on a regular basis. He has visited our laboratory twice and we have supplied him with data on the design and performance of terfenol actuators.

10. PUBLICATIONS

1. R. W. Brockett and Josip Loncaric, "The Geometry of Compliance Programming," in **Theory and Applications of Nonlinear Control Systems**, (C. I. Byrnes and A. Lindquist, Eds.), Elsevier Science Publishers, 1986.

2. Josip Loncaric, "Normal Forms of Stiffness and Compliance Matrices," **IEEE J. Robotics and Automation**, Vol. 3, No. 6, Dec. 1987, pp. 567-572.

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11. PERSONNEL

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12. PH.D. THESES BY PARTICIPATING PERSONNEL

1. Josip Loncaric, "Geometrical Analysis of Compliant Mechanisms in Robotics," Ph.D. Thesis, Harvard University, 1985.
2. David J. Montana, "Tactile Sensing and the Kinematics of Contact," Ph.D. Thesis, Harvard University, 1986.

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